US011469486B2

(12) **United States Patent**
Nadeau

(10) **Patent No.: US 11,469,486 B2**
(45) **Date of Patent: Oct. 11, 2022**

(54) **SURFACE MOUNT RADIO FREQUENCY CROSSOVER DEVICE**

(71) Applicant: **Knowles Cazenovia, Inc.**, Cazenovia, NY (US)

(72) Inventor: **Pierre Nadeau**, Fayetteville, NY (US)

(73) Assignee: **KNOWLES CAZENOVIA, INC.**, Cazenovia, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/699,187**

(22) Filed: **Nov. 29, 2019**

(65) **Prior Publication Data**

US 2021/0167478 A1 Jun. 3, 2021

(51) **Int. Cl.**

H01P 5/02 (2006.01)
H01P 3/08 (2006.01)
H05K 1/02 (2006.01)
H05K 1/18 (2006.01)

(52) **U.S. Cl.**

CPC ***H01P 5/02*** (2013.01); ***H01P 3/081*** (2013.01); ***H05K 1/025*** (2013.01); ***H05K 1/0242*** (2013.01); ***H05K 1/181*** (2013.01); *H05K 2201/10363* (2013.01)

(58) **Field of Classification Search**

CPC H01P 3/081; H01P 5/02; H05K 1/0242; H05K 1/025; H05K 1/181

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,321,375 A		6/1994	Corman	
6,734,750 B1		5/2004	Ostergaard	
6,949,819 B2 *		9/2005	Saito	H01R 31/08 257/692
2003/0206083 A1 *		11/2003	Takahashi	H01P 1/20363 333/247
2004/0256716 A1		12/2004	Saito et al.	
2008/0018391 A1		1/2008	Bates	
2008/0211601 A1		9/2008	Bates	

(Continued)

FOREIGN PATENT DOCUMENTS

CN	1184342 A	6/1998
CN	1430462 A	7/2003
DE	10 2015 115 819 A1	3/2017

OTHER PUBLICATIONS

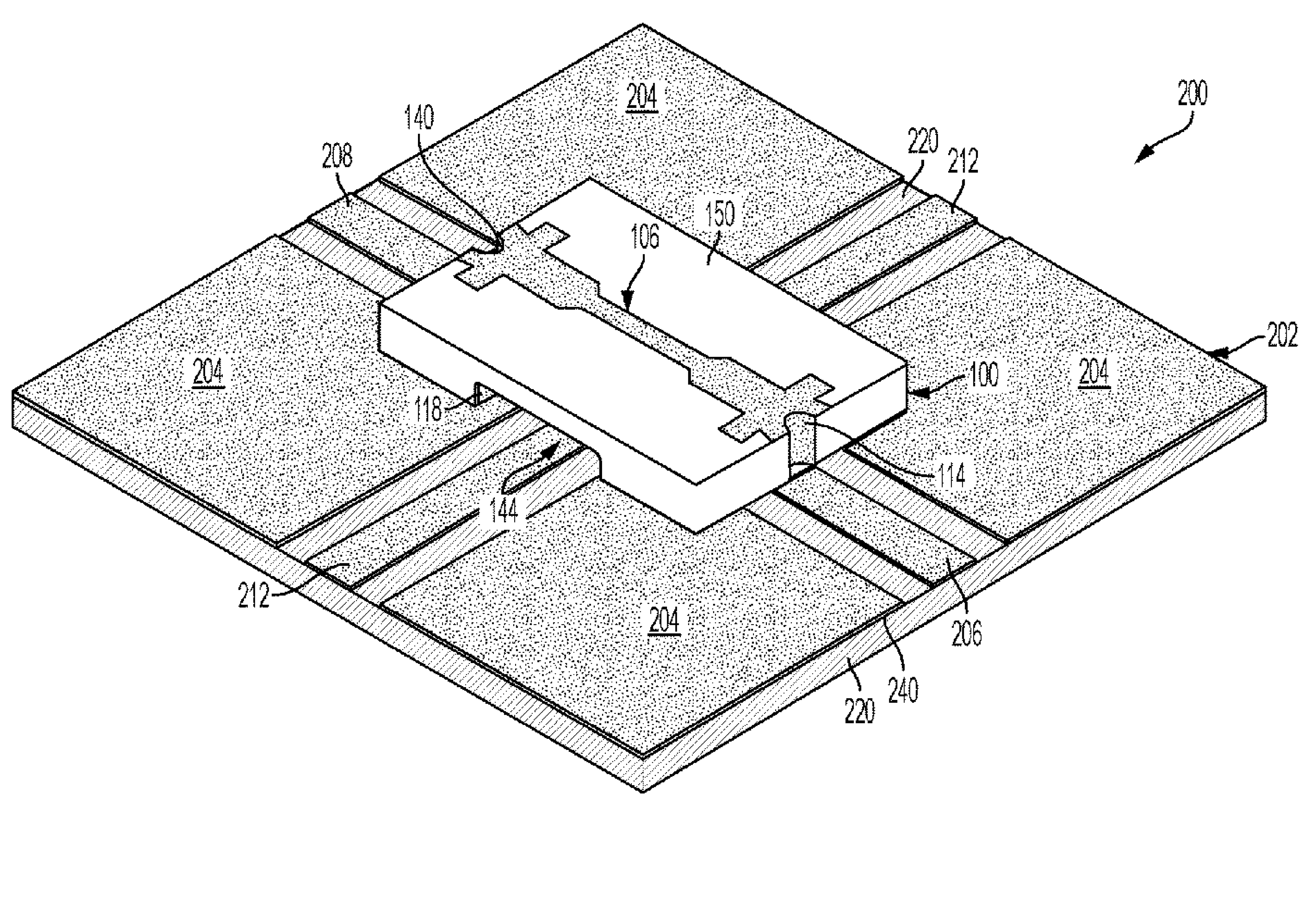
U.S. Appl. No. 17/013,504, filed Sep. 4, 2020, Burdick.
First Office Action for CN Appl. No. 202011362554.8, dated Jul. 1, 2022.

Primary Examiner — Samuel S Outten
(74) *Attorney, Agent, or Firm* — Foley & Lardner LLP

(57) **ABSTRACT**

A microwave or radio frequency (RF) device includes an insulating substrate having a first surface and a second surface opposing the first surface. The device also includes a crossover conductor disposed on the first surface extending between a first edge of the first surface and a second edge of the first surface. The device also includes a depression in the second surface defined at least in part by (i) a third surface recessed in relation to the second surface, and (ii) at least one sidewall that extends between the second surface and the third surface. The device further includes a conductive coating formed over at least a portion of the second surface, the third surface, and the at least one sidewall, where the conductive coating is insulated from the crossover conductor by the insulating substrate.

19 Claims, 5 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2009/0231064 A1		9/2009	Bates et al.
2013/0342287 A1		12/2013	Randall et al.
2014/0264287 A1	*	9/2014	Abraham H01P 7/086 257/31
2014/0306776 A1		10/2014	Eom et al.
2016/0049713 A1	*	2/2016	Ostergaard H01P 1/20345 333/238
2018/0183130 A1		6/2018	Bates
2019/0081378 A1		3/2019	Bates
2020/0021030 A1		1/2020	Bates
2020/0259263 A1		8/2020	Dani
2020/0358160 A1		11/2020	Alton
2020/0403286 A1		12/2020	Burdick

* cited by examiner

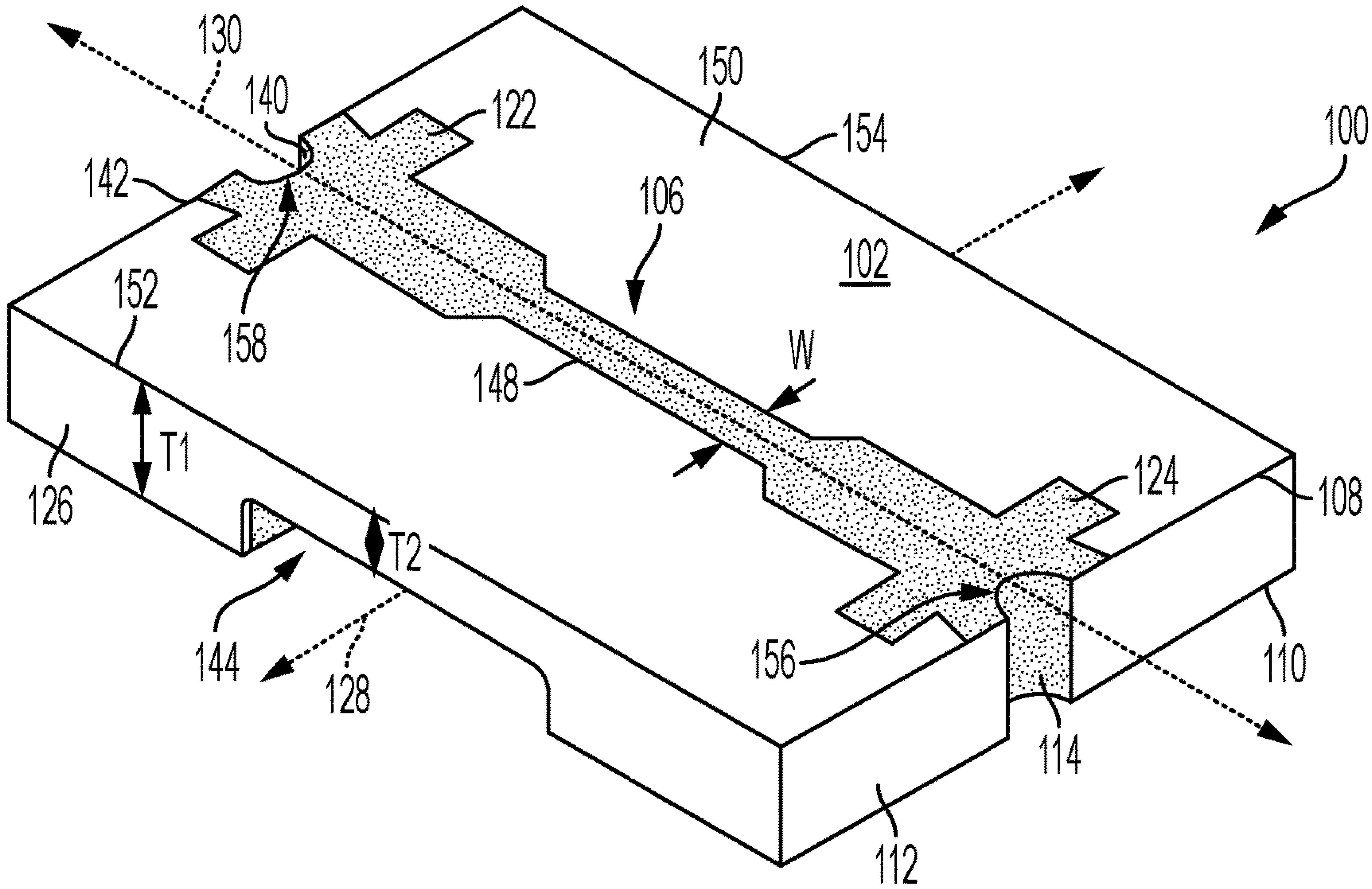

130
140
122
150
154
100
142
106
102
152
158
148
W
124
108
T1
126
T2
156
110
144
128
114
112

FIG. 1A

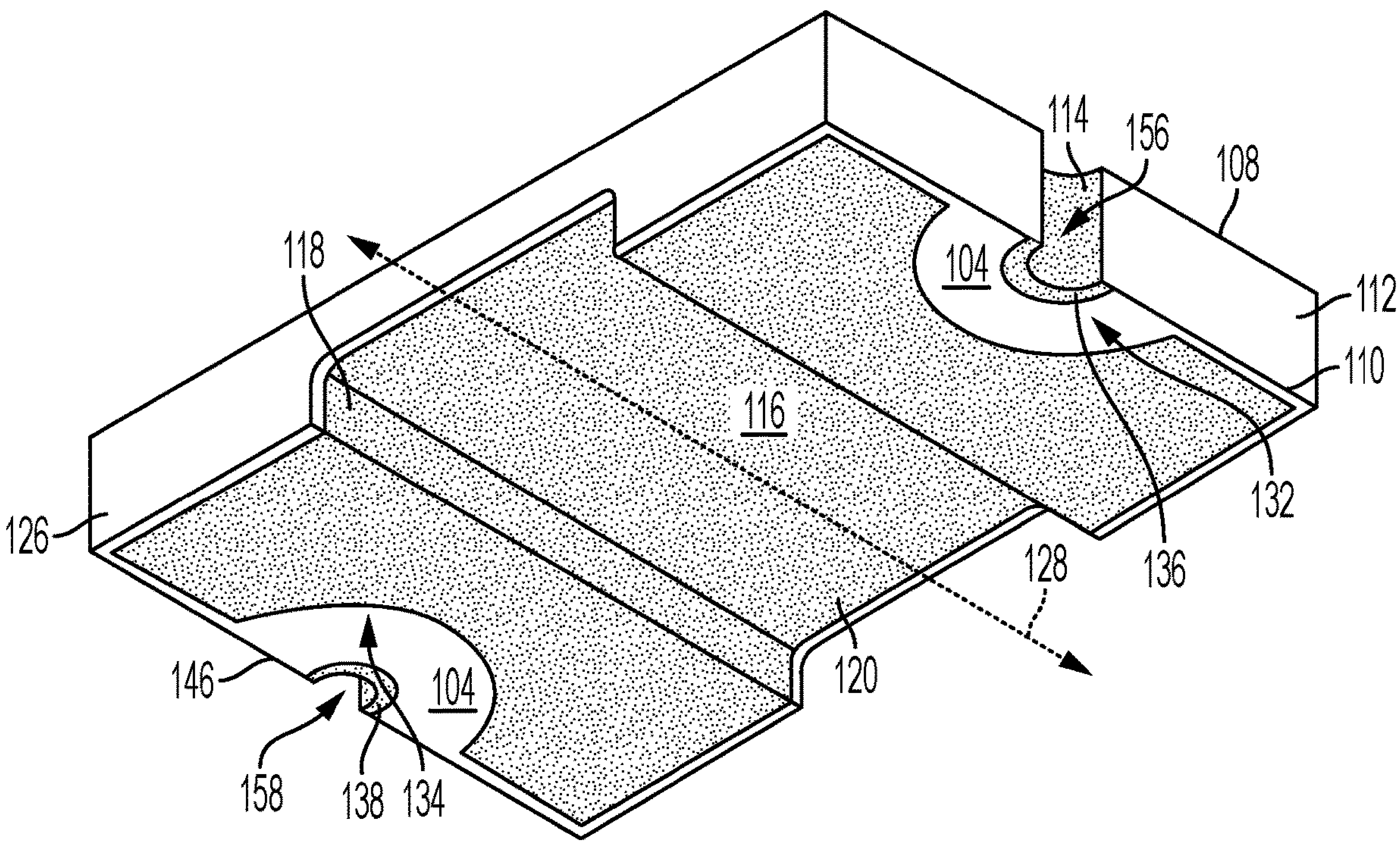

114
156
108
118
104
112
116
110
132
126
128
136
120
146
104
158
138
134

FIG. 1B

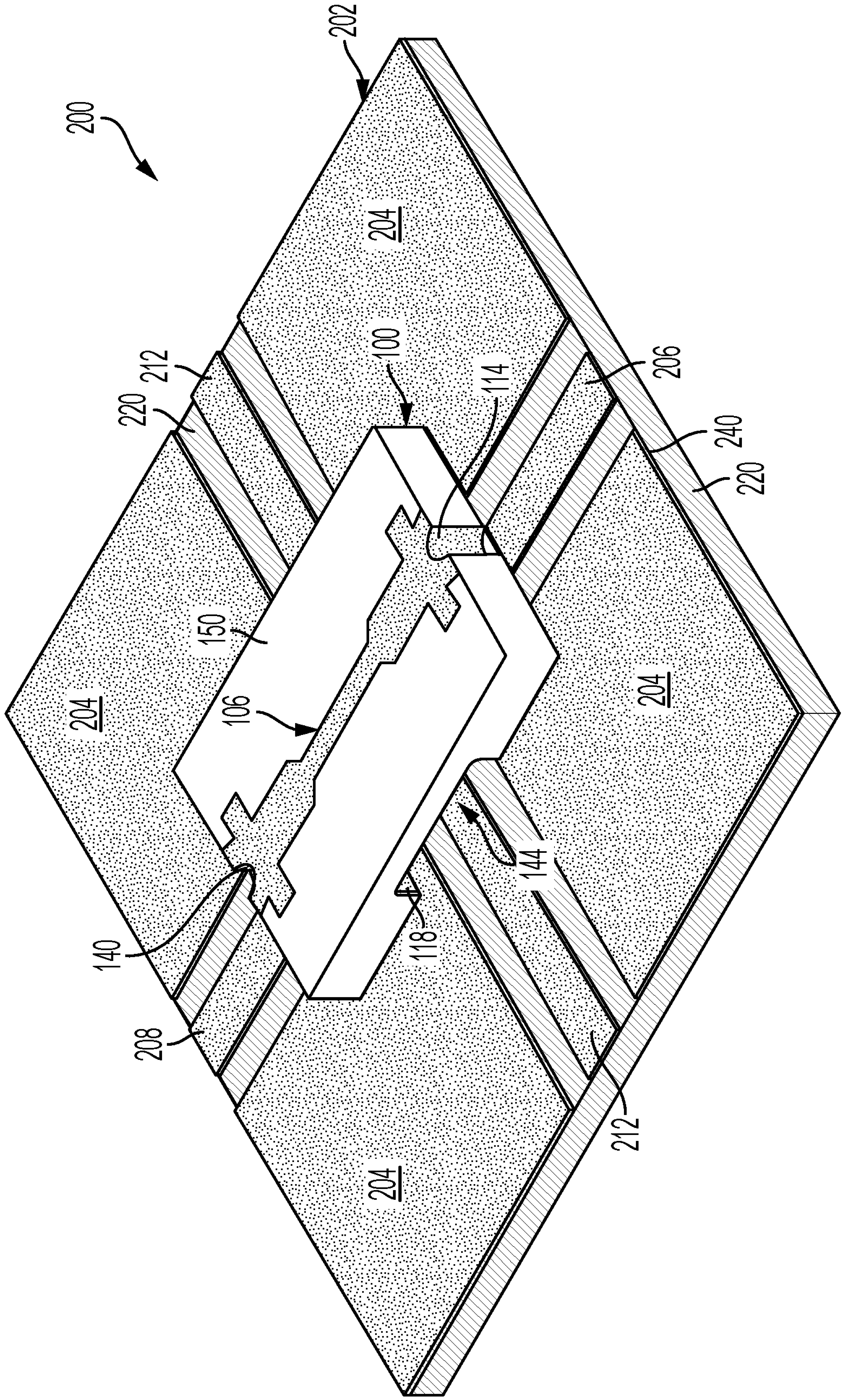

200
202
204
204
204
204
212
220
100
114
206
240
220
150
106
144
140
118
208
212

FIG. 2

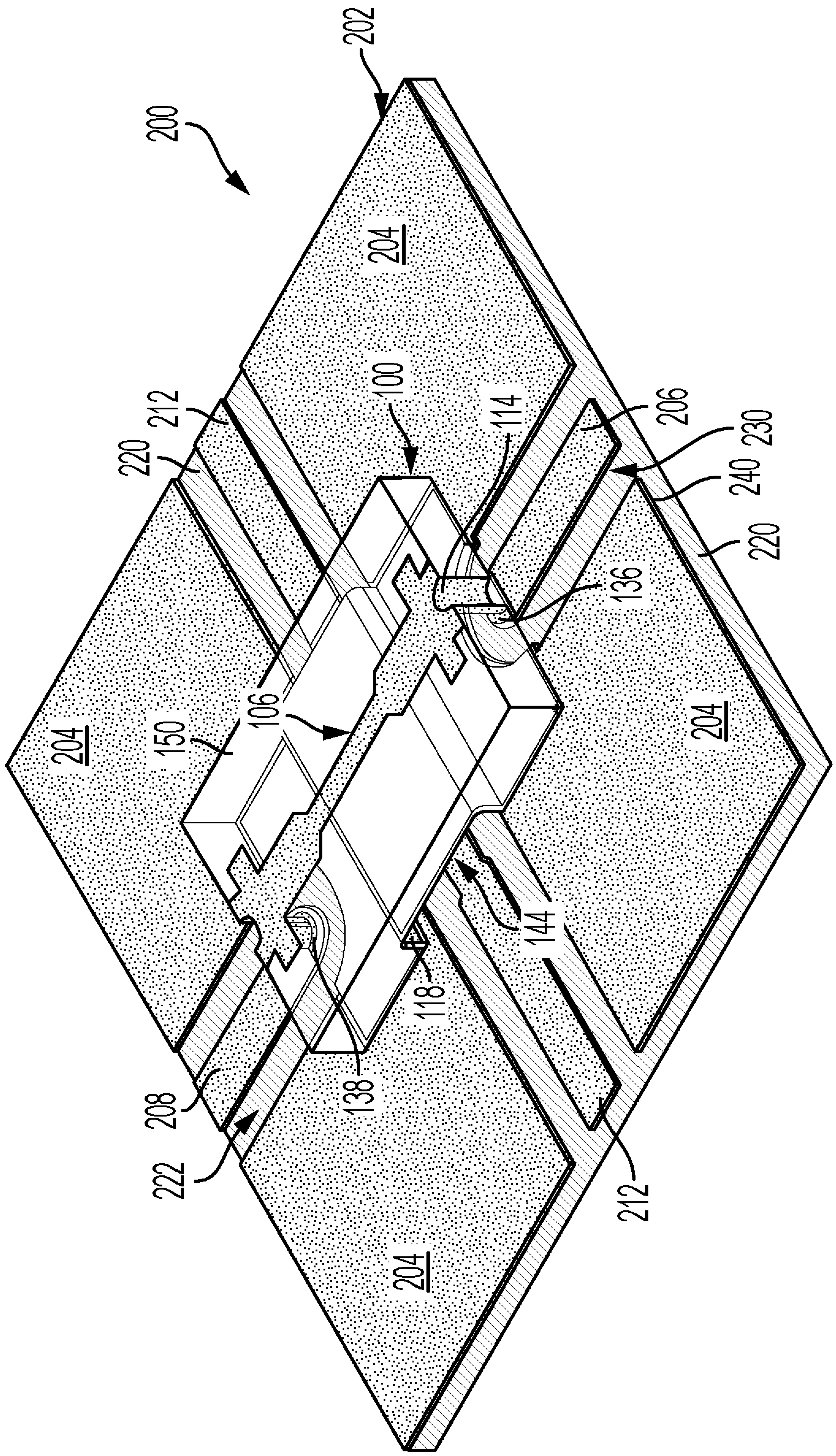

200
202
204
212
220
100
114
206
230
240
220
136
106
150
204
204
144
118
138
208
222
212
204

FIG. 3

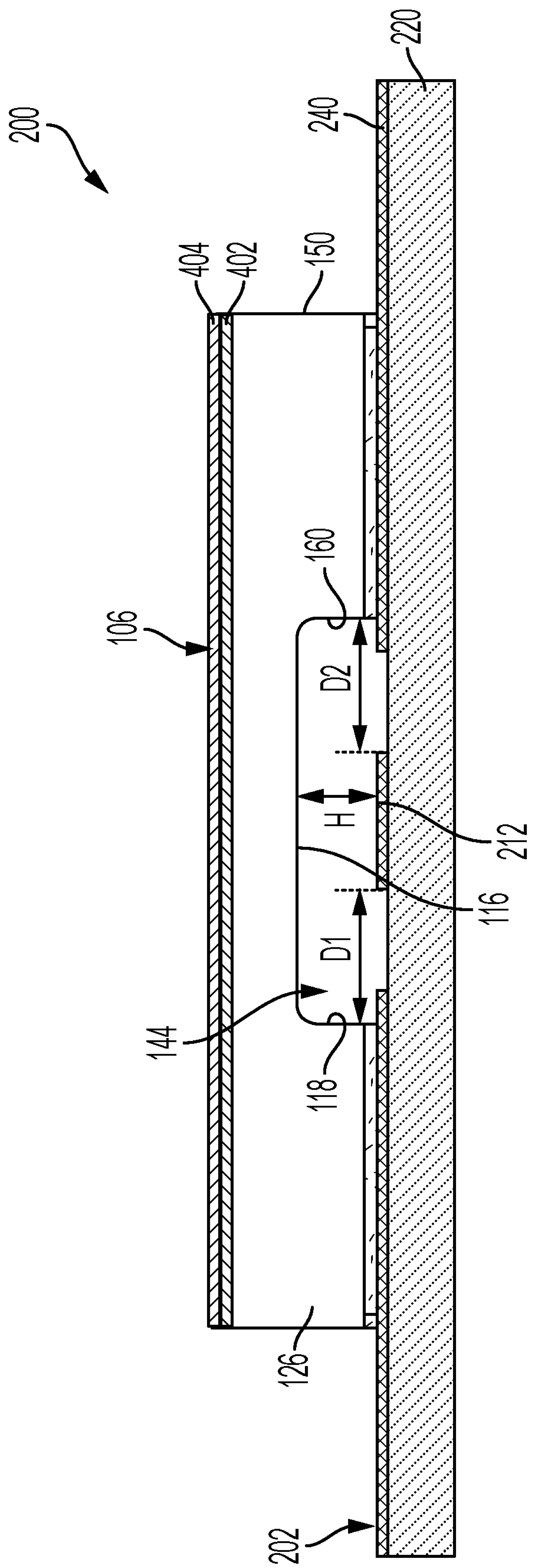


FIG. 4

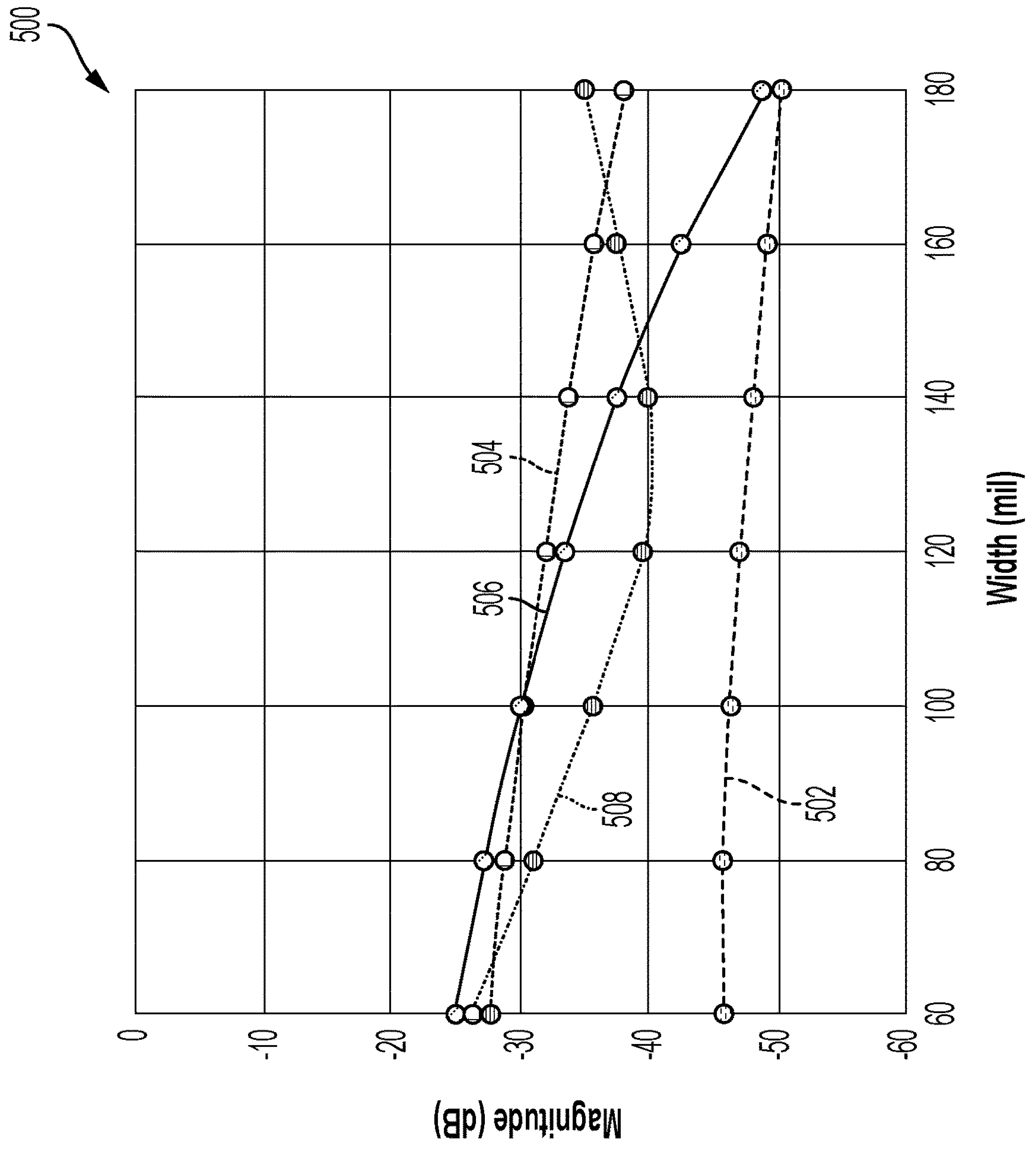

500
504
506
508
502
0
-10
-20
-30
-40
-50
-60
Magnitude (dB)
60
80
100
120
140
160
180
Width (mil)

FIG. 5

SURFACE MOUNT RADIO FREQUENCY CROSSOVER DEVICE

BACKGROUND

Microwave and radio-frequency (RF) circuits can incorporate the routing of transmission lines that interconnect RF components such as amplifiers, mixers and filters that are integrated on a substrate such as a printed circuit board. In some instances, transmission line paths on printed circuit boards may intersect, resulting in a need for crossover components.

SUMMARY

In an embodiment, a RF crossover device includes an insulating substrate having a first surface and a second surface opposing the first surface. The crossover device further includes a crossover conductor disposed on the first surface extending between a first edge of the first surface and a second edge of the first surface. The crossover device also includes a depression in the second surface defined at least in part by (i) a third surface recessed in relation to the second surface, and (ii) at least one sidewall that extends between the second surface and the third surface. The crossover device further includes a conductive coating formed over at least a portion of the second surface, the third surface, and the at least one sidewall, the conductive coating being insulated from the crossover conductor by the insulating substrate.

In some embodiments, the depression extends between two side surfaces of the insulating substrate. In some embodiments, the depression extends in a direction that is orthogonal to a direction in which the crossover conductor extends on the first surface. In some embodiments, the crossover device further includes a first transition conductor, conductively coupled with the crossover conductor, disposed on a first side surface of the insulating substrate, and a second transition conductor, conductively coupled with the crossover conductor, disposed on a second side surface of the insulating substrate.

In some embodiments, the first transition conductor extends between the first edge of the first surface and a first edge of the second surface, and wherein the second transition conductor extends between the second edge of the first surface and a second edge of the second surface. In some embodiments, the first side surface of the insulating substrate includes a first indented region, and wherein the first transition conductor is at least partially disposed over the first indented region. In some embodiments, the crossover device further includes a first crossover contact disposed on the second surface of the insulating substrate and coupled with the first transition conductor, a second crossover contact disposed on the second surface of the insulating substrate and coupled with the second transition conductor. In some embodiments, the first crossover contact is separated from the conductive coating on the second surface by a first crossover isolation region, and wherein the second crossover contact is separated from the conductive coating on the second surface by a second crossover isolation region.

In some embodiments, at least a portion of the crossover conductor includes a transmission line. In some embodiments, the crossover conductor includes at least one impedance matching structure positioned between the transmission line and at least one of the first edge and the second edge of the first surface. In some embodiments, the crossover conductor includes a plurality of metallic layers, wherein materials of at least two metallic layers of the plurality of metallic layers are different. In some embodiments, the plurality of metallic layers include metallic layers of at least two of copper, silver, gold, nickel, or titanium-tungsten alloy. In some embodiments, the conductive coating includes a plurality of metallic layers, wherein materials of at least two metallic layers of the plurality of metallic layers are different. In some embodiments, the insulating substrate includes at least one of a ceramic material, glass, sapphire, quartz or a printed circuit board material.

In some embodiments, a RF device includes a circuit board having a first surface and an opposing second surface. The RF device further includes a first RF conductor disposed on the first surface of the circuit board, the first RF conductor extending in a first direction. The RF device further includes a second RF conductor disposed on the first surface of the circuit board, the second RF conductor extending in a second direction, different from the first direction. The RF device also includes a ground conductor disposed on the first surface of the circuit board, the ground conductor electrically isolated from the first RF conductor and the second RF conductor. The RF device further includes the RF crossover device positioned on the circuit board. The conductive coating over the second surface of the insulating substrate makes contact with the ground plane. The first RF conductor passes under the depression in the second surface of the insulating substrate, and the second RF conductor is electrically coupled with the crossover conductor disposed on the first surface of the insulating substrate.

In some embodiments, the conductive coating on at least one sidewall is separated from the first RF conductor by a distance of between 15 mils and 25 mils. In some embodiments, the conductive coating on the third surface of the insulating substrate is separated from the first RF conductor disposed on the first surface of the circuit board by a distance of between 5 mils and 15 mils. In some embodiments, a magnitude of isolation between the first RF conductor and the crossover conductor is an increasing function of a width of the crossover conductor measured over the depression. In some embodiments, the crossover conductor is a first crossover conductor, and the RF device further includes a second crossover conductor disposed adjacent to the first crossover conductor over the first surface of the insulating substrate, where the second crossover conductor extends between the first edge and the second edge of the first surface.

The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the following drawings and the detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other features of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only several embodiments in accordance with the disclosure and are, therefore, not to be considered limiting of its scope, the disclosure will be described with additional specificity and detail through use of the accompanying drawings.

FIGS. **1**A and **1**B show isometric views of an example RF crossover device according to embodiments of the present disclosure.

FIG. **2** shows an arrangement including an example RF crossover device positioned over a printed circuit board (PCB).

FIG. **3** shows the arrangement shown in FIG. **2** including a transparent view of the insulating substrate.

FIG. **4** shows a side view of the arrangement shown in FIG. **2**.

FIG. **5** shows an example graph of a magnitude of minimum isolation between a crossover conductor and a crossed over RF transmission line plotted over various values of a width of the crossover conductor as well as different frequencies.

In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, and designed in a wide variety of different configurations, all of which are explicitly contemplated and make part of this disclosure.

DETAILED DESCRIPTION

The present disclosure describes devices and techniques for crossover components used in microwave or RF devices (collectively referred to herein as "RF devices"). The RF devices can include components such as conductors, transmission lines, filters, etc., that are formed on a substrate such as a printed circuit board. In some instances, paths of two or more RF transmission lines may intersect, resulting in a need for a crossover to allow one RF transmission line to cross the path of the other RF transmission line without making contact with the other RF transmission line. One approach to forming a crossover is to use multi-layered printed circuit boards, where the RF transmission lines are crossed over using multiple conductive and/or ground layers in the PCB. For example, the PCB can include multilayer stripline layers that can be connected through vias to provide crossover of RF transmission lines. However, such approaches suffer from a need to have multiple PCB layers, which drives the cost and manufacturing complexity of the overall PCB. Multilayer PCB's also suffer from poorer manufacturing tolerances, which make millimeter-wave operation unrealizable.

One solution, discussed in relation to the embodiments disclosed herein, provides a crossover device that includes a ceramic or other insulating substrate that forms a jumper over the (microstrip) RF transmission line that is to be crossed over. In particular, the crossover device includes a metallized tunnel, which can be positioned over the crossed over RF transmission line in order to provide the necessary isolation between the two traces. The crossover device can include at least one conductor over at least one surface of the crossover device isolated from the metallization on the tunnel to provide a conductive path for the crossing RF transmission line. The ceramic substrate can be a monolithic structure or block (e.g., of a single material) and can provide improved isolation between the crossed over and the crossing RF transmission lines. For example, the improved isolation can allow the RF components, or the circuits in which the RF components are incorporated, to operate at frequencies as high as 40 GHz.

FIGS. **1**A and **1**B show isometric views of an example RF crossover device **100**. The RF crossover device **100** includes an insulating substrate **150** having a first surface **102** and a second surface **104** opposing the first surface **102**. A plurality of side surfaces, of which a first side surface **112** and a third side surface **126** are shown in FIGS. **1**A and **1**B, can extend between the first surface **102** and the second surface **104**. In plan view, the first surface **102** and the second surface **104** have a rectangular shape. However, the first surface **102** or the second surface **104** can have shapes other than the rectangular shape shown in FIGS. **1**A and **1**B. In particular, the first surface **102** or the second surface **104** can have any polygonal shape (regular or irregular) or a circular or other shape. The shape of the first surface **102** and the second surface **104** in plan view may be different in some instances. The number of the plurality of side surfaces that extend between the first surface **102** and the second surface **104** can be a function of the shapes of the first surface **102** and the second surface **104**. The first surface **102** is planar, however, in some embodiments, the first surface **102** can be non-planar, and can include depression(s) or protrusion(s). The first surface **102** has a perimeter including a first edge **108**, a second edge **142**, a third edge **152**, and a fourth edge **154**. The first side surface **112** extends between the first edge **108** of the first surface and the second surface **104**, and the third side surface **126** extends between the third edge **152** of the first surface **102** and the second surface **104**. While not shown in FIGS. **1**A and **1**B, a fourth side surface extends between the fourth edge **154** and the second surface **104**.

The second surface **104** includes a depression **144**. The depression **144** is defined at least in part by a third surface **116** that is recessed in relation to the second surface **104**, a first depression sidewall **118** and/or a second depression sidewall (not shown) opposite the first depression sidewall **118**. In some embodiments, the depression **144** comprises one or more arches that is/are defined at least in part by a one or more curved surfaces that that is/are recessed in relation to the second surface **104**. The first depression sidewall **118** and the second depression sidewall can extend between the second surface **104** and the recessed third surface **116**. As discussed further below, the depression **144** allows for a crossed over RF transmission line to pass below the RF crossover device **100** when the RF crossover device **100** is positioned over a printed circuit board. The third surface **116** is planar. However, in some instances, the third surface **116** may be non-planar, such as, a curved or convex shaped. The third surface **116** extends between the third side surface **126** and the fourth side surface (not shown) opposite the third side surface. A portion of the fourth side surface extends between the fourth edge **154** of the first surface **102** and the second surface **104** and another portion of the fourth side surface extends between the fourth edge **154** and the third surface **116**. The RF crossover device **100** has a first thickness T**1** measured between the first surface **102** and the second surface **104**, and a second thickness T**2** measured between the first surface **102** and the third surface **116** of the depression **144**. The second thickness T**2** is less than the first thickness T**1**. The second thickness T**2** can be uniform along a longitudinal axis **128** of the depression **144**. In some embodiments, the thickness T**2** can be non-uniform along the longitudinal axis **128**. The first depression sidewall **118** and the second depression sidewall can extend normal to the second surface **104** and the third surface **116**, however, in some instances, the first depression sidewall **118** and the second depression sidewall can form a non-perpendicular angle with the second surface **104** and/or the third surface **116**.

A crossover conductor **106** is disposed on the first surface **102**, and extends between the first edge **108** and the second edge **142** of the first surface **102**. The crossover conductor **106** provides a conductive path for the crossing over RF transmission line (e.g., to carry a signal). A first transition conductor **114** is disposed on the first side surface **112**, and extends between the first edge **108** of the first surface **102** and a first edge **110** of the second surface **104**. The first transition conductor **114** makes electrical contact with the crossover conductor **106** at the first edge **108** of the first surface **102**. A second transition conductor **140** is disposed on a second side surface of the RF crossover device **100**. The second side surface extends between the second edge **142** of the first surface **102** and the second surface **104**. The second transition conductor **140** makes electrical contact with the crossover conductor **106** at the second edge **142** of the first surface **102**. As discussed below, the first transition conductor **114**, the crossover conductor **106** and the second transition conductor **140** provide a conductive path for a crossing over conductor disposed on a printed circuit board over which the RF crossover device **100** is disposed.

A first transition conductor **114** is disposed over the first side surface **112** and is coupled with the crossover conductor **106**. The first transition conductor **114** extends between the first edge **108** of the first surface **102** and a first edge **110** of the second surface **104**. The first transition conductor **114** provides a conductive path between the crossover conductor **106** and a RF transmission line positioned on the printed circuit board. Similarly, a second transition conductor **140** is disposed over the second side surface of the insulating substrate **150**, where the second side surface extends between the second edge **142** of the first surface **102** and a second edge **146** of the second surface **104**. The second transition conductor **140** provides a conductive path between the crossover conductor **106** and a RF transmission line positioned on the printed circuit board. The RF transmission line on the printed circuit board can be a crossing over RF component, and the combination of the first transition conductor **114**, the crossover conductor **106**, and the second transition conductor **140** can provide a conductive path (e.g., to carry a signal) to cross over another RF transmission line on the printed circuit board over which the crossover device **100** is positioned.

The first side surface **112** and the second side surface, which extend between the second edge **142** of the first surface **102** and the second edge **146** of the second surface **104**, can include a first indented region **156** and a second indented region **158**, respectively. At least a portion of the first transition conductor **114** is disposed over the first indented region **156** (or surface region), and at least a portion of the second transition conductor **140** is disposed over the second indented region **158** (or surface region). The first indented region **156** and the second indented region **158** can be a concave indentation (or surface region) in the first side surface **112** and the second side surface, respectively, of the insulating substrate **150**. In some embodiments, the first indented region **156** and the second indented region **158** can be a result of a manufacturing processing step (e.g., machining, milling, drilling) of the insulating substrate **150**. In some instances, multiple insulating substrates can be fabricated from a single larger insulating substrate. Holes can be drilled in the larger substrate, after which a metallization step can be carried out that can deposit at least the crossover conductor **106** and metallize the interior of the drilled holes. Thereafter, individual pieces of the insulating substrate can be diced by cutting along diameters of the drilled and metallized holes, such as for example along the first edge **108** and the second edge **142** of the first surface **102**, and along the third edge **152** and the fourth edge **154**. The resulting separated insulating substrate **150** can now include the indented regions **156** and **158** with metallization that forms the first and second transition conductors **114** and **140**. In some embodiments, the first side surface **112** and the second side surface may not include the indented regions **156** and **158**, and may instead be planar with the first and second transition conductors **114** and **140** disposed on a portion of the planar first and second side surfaces, respectively.

The crossover conductor **106** includes at least one transmission line **148** and at least one impedance matching structure, such as, for example, a first impedance matching structure **124** and a second impedance matching structure **122**. The impedance matching structure is positioned after the surface mount transition **114** to provide improved performance and negate the capacitive loading that is inherent from the transition via. The transmission line **148** can be structured to have a specific impedance value, such as, for example, 50 ohms. The first and the second impedance matching structures **124** and **122** can reduce the risk of return loss by matching the impedance of the first and second transition conductors **114** and **140**, respectively, to the impedance of the crossover conductor **106**. The specific structure of each of the first and the second impedance matching structure **124** and **122** shown in FIGS. **1**A and **1**B is only an example and non-limiting, and other structures can be employed to provide similar impedance matching functionality and/or to support operation at various frequencies.

The crossover conductor **106** is disposed on the first surface **102** of the insulating substrate **150** along a crossover conductor axis **130**. The crossover conductor axis **130** is parallel to the longitudinal axis of the insulating substrate **150**, for instance. However, the crossover conductor axis **130** can have any orientation. In particular, the crossover conductor axis **130** direction can be based on the positions of the first and second transition conductors **114** and **140**, which, in turn, can be positioned on the respective side surfaces of the insulating substrate **150** to match the positions of the connection points to the crossing over RF transmission line on the printed circuit board. For example, the crossover conductor **106** (and the crossover conductor axis **130**) can be oriented at an angle with respect to the edges or the longitudinal axis of the insulating substrate **150**. The direction of the crossover conductor axis **130** is substantially (e.g., within 5%) orthogonal to the direction of the longitudinal axis **128** of the depression **144**. However, in some instances, the angle between the crossover conductor axis **130** and the longitudinal axis **128** of the depression **144** can be non-orthogonal, such as when the depression is positioned obliquely in relation to the third and fourth side surfaces of the insulating substrate **150**.

The second surface **104** of the insulating substrate **150** can include a first crossover contact **136** and a second crossover contact **138**. The first crossover contact **136** is positioned along the first edge **110** of the second surface **104**, while the second crossover contact **138** is positioned along the second edge **146** of the second surface **104**. The first crossover contact **136** is conductively coupled with the first transition conductor **114** and the second crossover contact **138** is conductively coupled with the second transition conductor **140**. The first crossover contact **136** is positioned along a portion of the first edge **110** of the second surface **104** that forms a periphery of the first indented region **156**. The second crossover contact **138** is positioned along a portion of the second edge **146** of the second surface **104** that forms a periphery of the second indented region **158**. The first crossover contact **136** and the second crossover contact **138** can make contact with two ends (or portions or contact points) of a crossing over RF transmission line when the insulating substrate **150** is positioned on a printed circuit board. In some embodiments, the first crossover contact **136** and the second crossover contact **138** can be positioned anywhere over the second surface **104** of the insulating substrate **150**. Their positions can be dependent upon the positions of the contact points to the crossing over RF transmission line on the printed circuit board.

A conductive coating **120** (e.g., that provides electromagnetic shielding) is formed over at least a portion of the second surface **104**, the third surface **116** and at least one of the first depression sidewall **118** and the second depression sidewall. The conductive coating **120** can be formed of one or more metals or metal alloys. In the example shown in FIGS. **1**A and **1**B, the entire depression **144**, that is, the third surface **116**, the first depression sidewall **118**, and the second depression sidewall, is coated with the conductive coating **120**. In some other embodiments, only a portion of the depression **144** may be coated with the conductive coating **120**. For example, in some embodiments, the third surface **116** may be coated with the conductive coating **120**, and one or both of the first or second depression sidewalls may not be coated with the conductive coating **120**.

The conductive coating **120** provides a ground plane connection, and can be conductively coupled with the ground plane on the printed circuit board on which the crossover device **100** is mounted. The conductive coating **120** in the depression **144** provides shielding between the crossover conductor **106** and the crossed over conductor that passes through a tunnel formed by the depression **144** when the crossover device **100** is mounted on the printed circuit board. In some examples, the conductive coating **120** in the depression **144** can provide a 30 dB to 50 dB isolation between the crossover conductor **106** and the crossed over conductor on the printed circuit board.

In some examples, the conductive coating **120** can include coatings of one or multiple metals such as gold (Au), nickel (Ni), titanium (Ti), tungsten (W), copper (Cu), silver (Ag), etc. In some embodiments, the conductive coating **120** can include a layer of Au of thickness between 3 micro-inches and 6 micro-inches, a layer of Ni of thickness between 40 micro-inches and 80 micro-inches, another layer of Au of thickness between 75 micro-inches and 125 micro-inches, and a layer of titanium-tungsten alloy (TiW) of thickness between 200 angstrom and 400 angstrom. The Ni layer can provide a solderable trace or surface, which can improve the surface mount solder bonding of the crossover device to the printed circuit board.

The first crossover contact **136** and the second crossover contact **138** are physically isolated from the conductive coating **120** by a first crossover isolation region **132** and a second crossover isolation region **134**, respectively. The first and second crossover isolation regions **132** and **134** can be exposed portions of the second surface **104** of the insulating substrate **150** that are not covered by a conductive coating.

FIG. **2** shows an arrangement **200** including an example crossover device (e.g., that is shown in FIGS. **1**A and **1**B) positioned over a printed circuit board (PCB) **202**. The PCB **202** includes an insulating board **220** (also referred to as "circuit board") over which at least one metal layer **240** is disposed. The metal layer can be patterned to form a ground plane (or "ground conductor") **204**, a first portion **206** of a crossing over RF transmission line (also referred to as "a second RF conductor"), a second portion **208** of the crossing over RF transmission line, and a crossed over RF transmission line (also referred to as "a first RF conductor") **212**. The paths of the crossing over RF transmission line and the crossed over RF transmission line **212** can cross over or intersect by virtue of their different respective directions and/or pathways enabled by the crossover device **100**. The crossover device **100**, discussed above in relation to FIGS. **1**A and **1**B can be positioned over the PCB **202** such that the second surface **104** faces the PCB **202**. In particular, the conductive coating **120** makes contact with the ground plane **204** on the PCB **202**. Further, the depression **144** is positioned such that the crossed over RF transmission line **212** passes under the depression **144** without making contact with any conductive surface of on the crossover device **100**. For example, the crossed over RF transmission line **212** is separated (e.g., insulated or isolated) from the conductive coating on the depression sidewalls of the crossover device **100**. Further, the first transition conductor **114** is aligned with the first portion **206** (e.g., contact point) of the crossing over RF transmission line, and the second transition conductor **140** is aligned with the second portion **208** (e.g., contact point) of the crossing over RF transmission line. The arrangement **200** allows for the crossing over RF transmission line to cross over the crossed over RF transmission line **212** by incorporating the crossover device **100**.

FIG. **3** shows the arrangement **200** shown in FIG. **2** including a transparent view of the insulating substrate **150**. FIG. **3** shows the first crossover contact **136** in contact with the first portion **206** of the crossing over RF transmission line and the second crossover contact **138** in contact with the second portion **208** of the crossing over RF transmission line. Further, the conductive coating **120** on the second surface **104** of the crossover device **100** is in contact with the ground plane **204** on the PCB **202**. The PCB **202** includes a first PCB isolation region **230** that isolates or separates the first portion **206** from the ground plane **204**, and includes a second PCB isolation region **222** that isolates or separates the second portion **208** from the ground plane **204**. The first crossover isolation region **132** on the crossover device **100** coincides with the first PCB isolation region **230**, and the second crossover isolation region **134** on the crossover device **100** coincides with the second PCB isolation region **222**. Thus, the entire path of the crossing over RF conductor over the crossover device **100** is isolated from the ground plane (or the conductive coating **120**) on the crossover device **100** and on the PCB **202**.

FIG. **4** shows a side view of the arrangement **200** shown in FIG. **2**. In particular, FIG. **4** shows the side view of the PCB **202** with the crossover device **100** mounted on the PCB **202**. The crossed over RF transmission line **212** can be separated from the conductive coating **120** on the first depression sidewall **118** by a distance D**1**, and from the conductive coating **120** on the second depression sidewall **160** by a distance D**2**. Further, the crossed over RF transmission line **212** is separated (e.g., isolated or insulated) from the conductive coating **120** on the third surface **116** by a distance H. The larger are the distances D**1**, D**2**, and H, the better is the isolation between the crossed over RF transmission line **212** and the crossover conductor **106**. In some embodiments, the distances D**1** and D**2** can have values between 15 mils and 25 mils. In some embodiments, the distance H can have a value between 5 mils and 15 mils.

The crossover conductor **106** can include two or more metal layers. For example, the crossover conductor **106** shown in FIG. **4** has a first metal layer **402** and a second metal layer **404**. The first and second metal layers **402** and **404** can include coatings of multiple metals such as gold (Au), nickel (Ni), titanium (Ti), tungsten (W), copper (Cu), silver (Ag), etc. In some embodiments, the first or second metal layers **402** and **404** can include a layer of Au of thickness between 3 micro-inches and 6 micro-inches, a layer of Ni of thickness between 40 micro-inches and 80 micro-inches, a layer of Au of thickness between 75 micro-inches and 125 micro-inches, and/or a layer of titanium-tungsten alloy (TiW) of thickness between 200 angstrom and 400 angstrom.

Referring again to FIGS. **1A** and **1B**, the crossover conductor **106** can have a width W measured transverse to a length of the crossover conductor **106**. In some embodiments, the width W measured right above the depression **144** (or tunnel). For example, the width W of the crossover conductor **106** can be measured transverse to the crossover conductor axis **130** above the depression **144**. The width W of the crossover conductor can be selected based at least on the desired impedance value of the crossover conductor **106** and a thickness T**2** of the insulating substrate **150** over the depression. In some embodiments, the thickness T**2** is measured above the depression **144** (or tunnel). Typically, for a fixed impedance value, the width W can have an inverse relationship with the thickness T**2** of the insulating substrate **150**. In other words, the width W can be a decreasing function of T**2** for a fixed value of impedance, such that when the value of T**2** is increased, the value of W decreases for the fixed value of impedance. As an example, Equation (1) below establishes a relationship between the impedance Z of the crossover conductor **106** and parameters such as the width W and the thickness T**2**. Equations (2)-(7) provide expression for various variables in Equation (1).

$$z = \frac{n}{2\pi\sqrt{\varepsilon_{re}}}\ln\left[\frac{F}{u} + \sqrt{1+\left(\frac{2}{u}\right)^2}\right] \quad \text{Equation (1)}$$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10}{u}\right)^{-ab} \quad \text{Equation (2)}$$

$$u = W/T2 \quad \text{Equation (3)}$$

$$n = 120\pi \quad \text{Equation (4)}$$

$$a = 1 + \frac{1}{49}\ln\left(\frac{u^4 + \left(\frac{u}{52}\right)^2}{u^4 + 0.432}\right) + \frac{1}{18.7}\ln\left[1 + \left(\frac{u}{18.1}\right)^3\right] \quad \text{Equation (5)}$$

$$b = 0.564\left(\frac{\varepsilon_r - 0.9}{\varepsilon_r + 3}\right)^{0.053} \quad \text{Equation (6)}$$

$$F = 6 + (2\pi - 6)\exp\left[-\left(\frac{30.666}{u}\right)^{0.7528}\right] \quad \text{Equation (7)}$$

In the above equations, ε_r is the dielectric constant of the insulating substrate **150**.

In some embodiments, the isolation between the crossover conductor **106** and the crossed over RF transmission line (e.g., **212** in FIGS. **2-4**) can be a function of the width along a longitudinal axis **128** of the crossover component. In particular, the isolation can be an increasing function of the width of the crossover component. That is, the magnitude of isolation increases with the increase in width of the crossover component. In some instances, this relationship holds for a specific band of frequencies. FIG. **5** shows an example graph **500** of a magnitude of minimum isolation between the crossover conductor **106** and the crossed over RF transmission line **212** plotted over various values of the component width (in mils) of the crossover conductor **106**. The first plot **502** represents a frequency of 10 GHz, the second plot **504** represents a frequency of 20 GHz, the third plot **506** represents a frequency of 30 GHz, and the fourth plot **508** represents a frequency of 40 GHz. At least for frequencies up to 30 GHz, the magnitude of minimum isolation between the crossover conductor **106** and the crossed over RF transmission line **212** increases with an increase in the width W of the crossover conductor **106**.

While FIGS. **1A-4** show only a single crossover conductor **106** disposed over the first surface **102** of the insulating substrate **150**, in some embodiments, two or more crossover conductors can be disposed over the first surface to provide crossover capability to more than one RF transmission line. For example, additional crossover conductors **106** can be positioned adjacent to each other over the first surface **102** of the insulating substrate **150** to allow two crossing over RF transmission lines to cross over one or more crossed over RF transmission lines. The crossover conductors can extend between the first edge **108** and the second edge **142** of the first surface **102** of the insulating substrate **150**. The crossover device **100** can then include a corresponding numbers of transition conductors (e.g., **114** and **140**), crossover contacts (e.g., **136** and **138**) to connect to the portions of the corresponding crossing over RF transmission lines. Furthermore, the size or width of the depression **144** can be adjusted according to the number of crossed over conductors over which the crossover device **100** is placed, such that the distance D**1** and D**2** is maintained between the conductive coating **120** on the first and second depression sidewalls **118** and **160** and the nearest crossed over RF transmission line.

The herein described subject matter sometimes illustrates different components contained within, or connected with, different other components. It is to be understood that such depicted architectures are illustrative, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively "associated" such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as "associated with" each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being "operably connected," or "operably coupled," to each other to achieve the desired functionality, and any two components capable of being so associated can also be viewed as being "operably couplable," to each other to achieve the desired functionality. Specific examples of operably couplable include but are not limited to physically mateable and/or physically interacting components and/or wirelessly interactable and/or wirelessly interacting components and/or logically interacting and/or logically interactable components.

With respect to the use of plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.).

It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations).

Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B." Further, unless otherwise noted, the use of the words "approximate," "about," "around," "substantially," etc., mean plus or minus ten percent.

The foregoing description of illustrative embodiments has been presented for purposes of illustration and of description. It is not intended to be exhaustive or limiting with respect to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed embodiments. It is intended that the scope of the invention be defined by the claims appended hereto and their equivalents.

What is claimed is:

1. A radio frequency (RF) crossover device, comprising:

an insulating substrate having a first surface and a second surface opposing the first surface;

a crossover conductor disposed on the first surface;

a depression in the second surface extending between two side surfaces of the insulating substrate and defined at least in part by (i) a third surface recessed in relation to the second surface, and (ii) at least one sidewall that extends between the second surface and the third surface, wherein the crossover conductor includes: (a) a transmission line having an impedance based on a width of the transmission line and a thickness of the insulating substrate defined between the first surface and the third surface, and (b) an impedance matching structure disposed on the first surface above at least a portion of the second surface; and

a conductive coating formed over at least a portion of the second surface, the third surface, and the at least one sidewall, the conductive coating being electrically isolated from the crossover conductor by the insulating substrate.

2. The RF crossover device of claim **1**, further comprising:

a first transition conductor electrically connected to the crossover conductor on a first side of the depression and extending between the first and second surfaces of the insulating substrate; and

a second transition conductor electrically connected to the crossover conductor on a second side of the depression, opposite the first side of the depression, and extending between the first and second surfaces of the insulating substrate.

3. The RF crossover device of claim **2**, wherein the first transition conductor extends along a first side end of the insulating substrate between the first surface and the second surface, and wherein the second transition conductor extends along a second end surface of the insulating substrate between the first surface and the second surface.

4. The RF crossover device of claim **3**, wherein the first end surface of the insulating substrate includes a first indented region, and wherein the first transition conductor is at least partially disposed over the first indented region.

5. The RF crossover device of claim **2**, further comprising:

a first crossover contact disposed on the second surface of the insulating substrate and electrically connected to the first transition conductor; and

a second crossover contact disposed on the second surface of the insulating substrate and electrically connected to the second transition conductor.

6. The RF crossover device of claim **5**, wherein the first crossover contact is separated from the conductive coating on the second surface by a first crossover isolation region, and wherein the second crossover contact is separated from the conductive coating on the second surface by a second crossover isolation region.

7. The RF crossover device of claim **1**, wherein the crossover conductor includes a plurality of metal layers, wherein materials of at least two metallic layers of the plurality of metallic layers are different.

8. The RF crossover device of claim **7**, wherein the plurality of metallic layers include metallic layers of at least two of copper, silver, gold, nickel, or titanium-tungsten alloy.

9. The RF crossover device of claim **1**, wherein the conductive coating includes a plurality of metallic layers, wherein materials of at least two metallic layers of the plurality of metallic layers are different.

10. The RF crossover device of claim **9**, wherein the plurality of metallic layers include metallic layers of at least two of copper, silver, gold, nickel, or titanium-tungsten alloy.

11. The RF crossover device of claim **1**, wherein the depression extends in a direction that is non-parallel to a direction in which the crossover conductor extends on the first surface.

12. The RF crossover device of claim **1**, wherein the impedance of the transmission line is based on a ratio of the width of the transmission line and the thickness of the insulating substrate.

13. The RF crossover device of claim **1**, wherein the insulating substrate includes at least one of a ceramic material, glass, sapphire, quartz or a printed circuit board material.

14. The RF crossover device of claim **1**, wherein the impedance matching structure is positioned between the transmission line and at least one of a first edge and a second edge of the first surface.

15. A radio-frequency (RF) device comprising:

a circuit board having a first surface and an opposing second surface;

a first RF conductor disposed on the first surface of the circuit board, the first RF conductor extending in a first direction;

a second RF conductor disposed on the first surface of the circuit board, the second RF conductor extending in a second direction, different from the first direction;

a ground conductor disposed on the first surface of the circuit board, the ground conductor electrically isolated from the first RF conductor and the second RF conductor;

a RF crossover device positioned on the circuit board and including:

an insulating substrate having a first surface and a second surface opposing the first surface;

a crossover conductor disposed on the first surface;

a depression in the second surface extending between two side surfaces of the insulating substrate and defined at least in part by (i) a third surface recessed in relation to the second surface, and (ii) at least one sidewall that extends between the second surface and the third surface, wherein the crossover conductor includes: (a) a transmission line having an impedance based on a width of the transmission line and a thickness of the insulating substrate defined between the first surface and the third surface, and (b) an impedance matching structure disposed on the first surface above at least a portion of the second surface; and

a conductive coating formed over at least a portion of the second surface, the third surface, and the at least one sidewall, the conductive coating being insulated from the crossover conductor by the insulating substrate,

wherein the conductive coating over the second surface of the insulating substrate makes contact with the ground plane,

wherein the first RF conductor passes under the depression in the second surface of the insulating substrate, and

wherein the second RF conductor is electrically connected to the crossover conductor disposed on the first surface of the insulating substrate.

16. The RF device of claim **15**, wherein the conductive coating on the at least one sidewall is separated from the first RF conductor by a distance of between 15 mils and 25 mils.

17. The RF device of claim **15**, wherein the conductive coating on the third surface of the insulating substrate is separated from the first RF conductor disposed on the first surface of the circuit board by a distance of between 5 mils and 15 mils.

18. The RF device of claim **15**, wherein a magnitude of isolation between the first RF conductor and the crossover conductor is an increasing function of a width of the crossover conductor measured over the depression.

19. The RF device of claim **15**, wherein the crossover conductor is a first crossover conductor, the RF device further comprising:

a second crossover conductor disposed adjacent to the first crossover conductor over the first surface of the insulating substrate.

* * * * *